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A NEW RADAR TECHNIQUE FOR SATELLITE RAINFALL ALGORITHM DEVELOPMENT

by

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ABSTRACT

The purpose of this research was to investigate a potential new radar parameter for measuring rainfall, namely the summation of the phase shifts at horizontal and vertical polarizations, $(\phi_H + \phi_V)$, due to propagation through precipitation. The proposed radar technique has several potential advantages over other approaches because it is insensitive to the drop size distribution and to the shapes of the raindrops. Such a parameter could greatly assist the development of satellite rainfall estimation algorithms by providing comparative measurements near the ground. It could also provide hydrologically useful information for such practical applications as urban hydrology.

Results of this investigation showed, however, that $(\phi_H + \phi_V)$ can not be measured by radar. However, a closely related radar parameter [propagation differential phase shift, $(\phi_H - \phi_V)$] can be readily measured using a polarization diversity radar. While it too is insensitive to the drop size distribution, it is a function of the mean shape of the raindrops. This dependence of $(\phi_H - \phi_V)$ on raindrop shape, however, can be accounted for when estimating the rain water content (W) by using simultaneously measured differential reflectivity and the magnitude of the cross-correlation function between horizontally and vertically co-polarized backscattered waves. Differential propagation phase shift, therefore, has the potential to be an important new tool for the radar measurement of rainfall.

It is recommended that propagation differential phase shift be further investigated and developed for radar monitoring of rainfall using a polarization agile radar such as that at Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt in the Federal Republic of Germany.

It is further recommended that a prototype multiple frequency microwave link be constructed for attenuation measurements not possible by existing radar systems. Both approaches can potentially provide the necessary data for improving our fundamental understanding of the physics and the limitations of the measurement of precipitation through remote sensing. Such knowledge will not only promote the formulation of better algorithms for precipitation measurement from satellites, but it can also potentially provide better rainfall measurements for hydrological applications especially in locations where the placement of rain gauge networks is logistically or fiscally impractical.

1. Introduction

The improved measurement of rainfall is not only important to many human activities such as agriculture and urban hydrology, but it is also vital for advancing our understanding of the response of the atmosphere to latent heat release from local to global scales. The latent heat released in the tropics is a principal component of the general circulation of the atmosphere of the earth. Unfortunately accurate measurements of the rainfall in the tropics are practically non-existent since most of the tropics is oceanic and, therefore, not amenable to the usual land based rainfall measurement techniques. The only alternative is to obtain the necessary rainfall measurements through remote sensing.

Recently it has been proposed that radiometric measurements from satellites could be used to estimate tropical rainfall on a global scale. Unlike raingages, however, the radiometers do not measure rainfall directly. Rather the rainfall must be inferred from brightness temperatures (Wilheit et al., 1977) measured at several frequencies. But brightness temperatures are the result of several interactive processes which include not only the desired upwelling radiation from rain but also the scattering effect of ice lying between the rain and the satellite. Although the essential physics of these processes are known, the detailed understanding required for translating brightness temperatures into accurate estimates of rainfall needs refinement. For the next several years, a great amount of effort must be expended in the development of algorithms for estimating rainfall from satellite radiometric measurements if the dream of global rainfall measurements over the tropics is to become a reality.

The development of these algorithms, however, will require rainfall measurements which can be used as a standard for comparison. Although, in principle, a dense network of raingages might be sufficient over land, the satellite radiometric measurements are best suited for oceanic observations. It will, therefore, eventually be necessary to use earth bound remote sensing techniques which can provide measurements for rainfall intercomparisons over oceans.

2. Radar Parameters for Estimating Rainfall

Over the last several decades a number of radar sensing techniques for rain measurements have been proposed. In total these methods essentially exploit all the fundamental properties, namely frequency, amplitude, phase, and polarization of electromagnetic waves scattered in both the forward and backward directions. All of the measurable quantities are proportional to averages over the drop size distribution of different powers of the drop diameter (D).

The quantities of particular relevance to precipitation are rain water content (W), which is proportional to the average D^3 , and the rainfall rate in still air (R_0) which is nearly proportional to the average $D^{3.6}$. For most of the remote sensing parameters, the rain mass (either W or R_0) can only be estimated by interpolation between two or more measurements associated with an average D^n where $n \neq 3$ and $n \neq 3.6$.

Such interpolations, however, require assumptions about the form of the drop size distribution which, in general, is not known. It is well known, however, that there can be extreme and often rapid random as well as slower systematic variations in the drop size distribution. This variability is likely at times to introduce significant errors in rainfall estimates when using interpolations. In order to avoid the effect of drop size distribution variability, it is preferable, if possible, to measure parameters which are directly related either to W or R_0 .

There are only two parameters which are known to be directly proportional to the drop size distribution average D^3 . The first is propagation differential phase shift at wavelengths greater than 2.2 cm. As a transmitted wave propagates through precipitation, which is usually not spherical, the relative phase between the transmitted wave and the forward scattered wave from each particle is shifted slightly from zero. The shift also depends upon whether the polarization is horizontal or vertical. The addition to the transmitted wave of the forward scattered waves from all the particles causes the net propagating wave to become more and more shifted in phase. The difference between this phase shift for a horizontally polarized wave from that for a vertically polarized wave is called the differential propagation phase shift. It has been shown (Jameson 1985) that for wavelengths greater than about 3 cm that the rate of change of this quantity with increasing distance (range) from the radar (Φ_{HV}) is given by

$$\Phi_{HV} = C W (1 - \beta) \quad (1)$$

where C is a constant dependent on the wavelength, W is the rain water content, and β is the mass weighted mean axis ratio of the raindrops over the drop size distribution using the generally accepted oblate approximation to actual raindrop shapes. Although β is not known, it can be approximated to within ± 0.01 using R , the reflectivity weighted mean axis ratio calculated from differential reflectivity (Jameson, 1983a).

Alternatively, if one could add rather than subtract the phase shifts corresponding to each polarization, it has been shown (Jameson, 1987) that

$$\Sigma\phi = C W \quad (2)$$

where $\Sigma\phi$ is the range rate of change of the summation of the two phase shifts. Unlike Φ_{HV} , the use of $\Sigma\phi$ does not require estimating β .

The important advantage of these two measurements (Φ_{HV} and $\Sigma\phi$) is that they are insensitive to variations in the drop size distribution since both are the result of complete integration over the drop size distribution regardless of its form.

The primary objective of the Phase I effort was to attempt to measure $\Sigma\phi$ using a polarization diversity radar in order to provide better ground rainfall measurements for comparison with rainfall

estimates using satellite retrieval algorithms. In particular, it was proposed to measure $(\phi_H + \phi_V)$ as a function of range, where $\phi_{H,V}$ are the propagation phase shifts at horizontal and vertical polarizations, respectively. As a result of this Phase I investigation, it appears, however, that while $(\phi_H - \phi_V)$ and, hence, Φ_{HV} can be measured by radar (Sachidananda and Zrnic', 1986b; Jameson and Hermant, 1987), $(\phi_H + \phi_V)$ and Σ_ϕ can not. These results are discussed in greater detail in the next section.

3. Phase I Investigation

3.1 The Radar Measurement of Σ_ϕ

Initial theoretical work suggested that it should be possible to measure Σ_ϕ using radar measurements of

$$\arg_1(\Pi_{HV}) = 2(\phi_H + \phi_V)_1 + 2\psi(r_1) + 2\psi_0 + (\delta_H + \delta_V)_1 \quad (3)$$

at increasing distances from the radar. Here $\psi(r_1)$ is the phase change due to the atmospheric index of refraction out to the range r_1 from the radar, ψ_0 is the mean initial phase of the transmitted waves, $(\delta_H + \delta_V)$ is the sum of the phase shifts produced during scattering, and

$$\Pi_{HV} = \frac{1}{M} \sum_{m=1}^M [E_{HH}(t_0 - \tau) E_{VV}(t_0) E_{VV}(t_0) E_{HH}(t_0 + \tau)]_m \quad (4)$$

where E_{HH}, E_{VV} are the backscattered co-polarized (identical polarization of the received and the transmitted waves) signals, t_0 is some initial time, and τ is the time interval between pulses (the interpulse period). By using E_{HH} measured at $\pm\tau$, the effect of the mean Doppler velocity of the particles can be cancelled.

From (3) it follows that

$$(r_2 - r_1)\xi(\Sigma_\phi) = \arg_2(\Pi_{HV}) - \arg_1(\Pi_{HV}) \quad (5a)$$

$$= 2[(\phi_H + \phi_V)_2 - (\phi_H + \phi_V)_1] + 2[\psi(r_2) - \psi(r_1)] + [(\delta_H + \delta_V)_2 - (\delta_H + \delta_V)_1] \quad (5b)$$

where $\xi(\Sigma_\phi)$ is the estimate of Σ_ϕ . Since the δ term is anticipated to be much smaller than the ϕ term when the wavelength is large with respect to the size of the raindrops (the so-called Rayleigh-Gans scattering regime), all that is required to estimate Σ_ϕ is an accurate measurement of the ψ term. Analysis reveals, however, that the electronic timing for setting the ranges of the data bins would have to be accurate to within a few picoseconds (10^{-12} sec) in order to properly locate the bin position to within a few degrees. This accuracy is not generally available in current radars.

A more serious limitation, however, was detected using numerical simulations of the backscattering of waves from an ensemble of raindrops. While waiting for completion of calibrations of the DFVLR

(Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt e.V.) radar, numerical experiments were performed in which a small but significant number of oblate raindrops were allowed to move according to a Gaussian distribution of particle velocities having a non-zero mean speed with respect to the radar. These experiments revealed that while $(\phi_H - \phi_V)$ could be measured and while the effect of the mean Doppler velocity on estimates of $(\phi_H + \phi_V)$ could indeed be removed as anticipated, there remained an unexpected and apparently arbitrary component of the phase. Expression (3) should be rewritten as

$$\arg(\Pi_{HV}) = 2(\phi_H + \phi_V) + 2\psi(r) + 2\psi_0 + (\delta_H + \delta_V) \quad (6)$$

where $\psi(r)$ is the arbitrary phase at range r apparently due to a net non-zero mean of phase position of the particles. Although this finding requires confirmation using actual radar observations, at this time there is no reason to believe that it is an artifact of the numerical experiments.

By combining quantities and ignoring the δ term with respect to the other considerably larger terms, (6) can be rewritten as

$$\arg(\Pi_{HV}) = 2(\phi_H + \phi_V) + 2\psi \quad (7)$$

This expression constitutes one equation with two unknowns. In order to determine $(\phi_H + \phi_V)$ is necessary and sufficient to find an additional equation of the form

$$\chi = a(\phi_H + \phi_V) + b\psi, \quad a \neq b \quad (8)$$

Although superficially the task is straightforward, in reality it is difficult to find a measurement with this form. To illustrate, consider the technique of transmitting either horizontal or vertical polarization while receiving the cross-polarized (the polarization of the received wave is orthogonal to that transmitted) return signals. The propagation phase shift of the cross-polarized wave is simply $(\phi_H + \phi_V)$ (eg., Jameson, 1985) so that $a=1$ in (8). Unfortunately, since this signal is produced by only one backscatter process $b=1$ as well. This approach, therefore, does not produce an equation which is independent of (7).

More generally it appears that polarization measurements cannot yield equations like (8). Since all elliptical polarizations are produced by adding a horizontally and a vertically polarized component with some phase shift, it follows that all backscattered elliptical waves can similarly be decomposed into horizontally and vertically polarized components. However, since each linear component has undergone a phase shift identical to that as if it had been transmitted independently of the other linear component, the results, as far as the phase measurements are concerned, are identical to (7).

The only other way to try to produce $a \neq b$ in (8) is to use measurements at different frequencies. At a particular polarization (horizontal or vertical) and at a particular wavelength λ_i (or equivalently frequency), removal of the Doppler velocity component

(Jameson and Mueller, 1985; Sachidananda and Zrnic', 1986a) leaves the phase of the backscattered wave given by

$$\phi_i = \phi_o + \phi_i^L + \frac{\eta L 4\pi}{\lambda_i} + 2\phi_i^P + \delta_i \quad (9)$$

where ϕ_o is the mean phase at transmission, ϕ_i^L is the random net phase of the distributed scatterers at distance L from the radar, η is the mean index of refraction of the atmosphere along L , ϕ_i^P is the mean propagation phase shift due to precipitation, and δ_i is the mean phase shift induced by backscattering. For wavelengths larger than about 2 cm η is independent of frequency (eg., Hinkle, 1987), and most raindrops will be Rayleigh-Gans scatterers so that $\phi_j^P = \phi_i^P \lambda_i/\lambda_j$, $\phi_j^L = \phi_i^L \lambda_i/\lambda_j$, and $\delta_i \approx \delta_j$. It follows that

$$\phi_i - \phi_j = \phi_i^L \left\{ 1 - \frac{\lambda_i}{\lambda_j} \right\} + \frac{4\pi\eta L}{\lambda_i} \left\{ 1 - \frac{\lambda_i}{\lambda_j} \right\} + 2\phi_i^P \left\{ 1 - \frac{\lambda_i}{\lambda_j} \right\} \quad (10)$$

This equation contains 3 unknowns ($\phi_i^L, \eta L, \phi_i^P$). It appears that by using two other wavelengths λ_k, λ_l one could form a system of three equations and, hence, solve for ϕ_i^P . Unfortunately because λ_i and λ_j only appear as a coefficient in front of each term on the right-hand side of (10), the equations in such a system would not be independent (only being multiples of each other). Although it is tempting to consider using $\lambda < 2$ cm in order to circumvent this situation (since then $\phi_j^P \neq \phi_i^P \lambda_i/\lambda_j$), $\Sigma\phi$ will no longer depend upon D^3 . Consequently the unique relation between W and $\Sigma\phi$ will be lost. It appears, therefore, that radars are not capable of measuring $\Sigma\phi$.

3.2 The Measurement of $\Sigma\phi$ Along a Microwave Link

Another possibility might be to try to measure $\Sigma\phi$ using a microwave link. For one polarization, either horizontal or vertical, let ϕ represent the phase angle measured at the microwave link receive after propagating along the path of length L . Expression (9) may then be simplified to

$$\phi_i = \phi_i^o + \frac{\eta L 2\pi}{\lambda_i} + \phi_i^P \quad (11)$$

where the subscript i denotes different wavelengths, ϕ_i^o is the original phases at the moment of transmission, and ϕ_i^P is the phase change induced by the precipitation. For $\lambda \geq 2$ cm the atmospheric index of refraction (η) is nearly independent of frequency. Hence, by using sufficiently long wavelengths and by using a common coherent reference source for generating the transmissions at the selected harmonic frequencies it follows from (11) that

$$\phi_i - \phi_j = \phi_i^o \left\{ 1 - \frac{\lambda_i}{\lambda_j} \right\} + \frac{\eta L 2\pi}{\lambda_i} \left\{ 1 - \frac{\lambda_i}{\lambda_j} \right\} + \phi_i^P \left\{ 1 - \frac{\lambda_i}{\lambda_j} \right\} \quad (12)$$

This expression is exactly analagous to (10). Therefore, for precisely the same reasons that (10) could not be used to measure Σ_ϕ , so (12) ca not be used either. However, as shall be discussed in section 4.2, a microwave link can still play an irreplaceable role in rainfall measurement.

4. Recommendations for Phase II

4.1 Radar Measurements

It is recommended that the rate of propagation differential phase shift (Φ_{HV}) be used to estimate the rain water content (W) through the relation (Jameson, 1985)

$$\xi(W) = \frac{\Phi_{HV}}{C(1-\beta)} \quad (13)$$

where W is in $g\ m^{-3}$, Φ_{HV} is in $deg\ km^{-1}$ (one-way), and $C=0.1493$ and 0.07857 for $\lambda=10.71$ and 5.45 cm, respectively. The mass weighted mean axis ratio (β) can be replaced by the reflectivity (power) weighted mean axis ratio R (Jameson, 1983a) to within an accuracy of ± 0.01 (Jameson, 1985) from

$$R = \zeta^{-3/7} \rho_L^{6/7} \quad (14)$$

(Jameson, 1983a; 1987a) where

$$\zeta = \frac{|E_{HH}|^2}{|E_{VV}|^2} \quad (15a)$$

$$\rho_L = \frac{|\langle E_{HH}^* E_{VV} \rangle|}{\left\{ |E_{HH}|^2 |E_{VV}|^2 \right\}^{0.5}} \quad (15b)$$

E_{HH} , E_{VV} are the backscattered co-polarized waves corresponding to horizontal and vertical polarizations, respectively, and * denotes complex conjugation.

Although Φ_{HV} provides a measure of W, it can also be used to estimate the rainfall rate in still air (R_0) if the relationship between drop size and axis ratio is known. Many such relationships appear to be of the form $r = a-bD$ (eg. Pruppacher and Beard, 1970; Jameson, 1983b). In addition an analysis by Sekhon and Srivastava (1970) revealed the simple relation

$$R_0 = 3.6 W V_0 \quad (16)$$

where V_0 [m sec⁻¹] is the fall speed of the median volume drop size over the ensemble of drops, W [g m⁻³] is the rain water content, and R_0 [mm hr⁻¹] is the rainfall rate. Combining (13) and (16) it follows that

$$\xi(R_0) = \frac{3.6 \Phi_{HV}}{C (1-R)} \xi(V) \quad (17)$$

where $\xi(V)$ is an estimate of mass weighted mean velocity (V) which is nearly identical to V_0 . Since V is a function of drop size, it can be estimated by first determining the reflectivity weighted mean axis ratio R calculated using (14). Combining R with the linear relation between drop size and axis ratio, the reflectivity weighted mean drop size can be determined. From the relationship between drop size and terminal fall speed (Gunn and Kinzer; 1949)

$$\xi(R_0) = \frac{3.6 \Phi_{HV}}{C (1-R)} \left\{ 9.45 \left\{ 1 - \exp[-6.6\{(a-R)/b\}] - 3\{(a-R)/b\} \exp[-14\{(a-R)/b\}] \right\} \right\} \quad (18)$$

where the bracketed term is an analytic fit by Fujita to the Gunn and Kinzer data, and a, b are constants equal to 1.03 and 0.62, respectively, when the drops are equilibrium shaped (Pruppacher and Pitter, 1971).

Measurement of Φ_{HV} and ζ require a radar capable of observations at different polarizations (a so-called polarization diversity radar). Such a radar has several advantages since it is then possible to estimate W and R_0 by several different methods. For example, Sachidananda and Zrnic' (1986b) suggest an alternative to (18) using Φ_{HV} and ζ for estimating R_0 . In addition ζ in combination with the reflectivity factor (Z) can be used to produce another independent estimate of R_0 (Seliga and Bringi, 1976). An additional estimate combining ζ , Z , and ρ_L can also be computed (Jameson, 1983b; Jameson and Hermant, 1987). This redundancy of techniques can be used to detect suspicious estimates. For example, in a recent analysis (Jameson and Hermant, 1987) of polarization data from the 10 cm Alberta Research Council circularly polarized radar, melting small hail produced an enhanced Z in conjunction with ζ relatively close to unity. Measurements of Φ_{HV} were also extracted from the data using a new technique (Jameson and Hermant, 1987). Estimates of R_0 and W using ζ and Z were found to be highly inflated with respect to values estimated using Φ_{HV} which are independent of Z . Apparently the melting process produced enhanced Z . Because ζ was near unity and, hence, R as well, the deduced mean drop size was probably underestimated. In order to produce the observed Z , unnatural concentrations of raindrops were,

therefore, required. Hence, R_0 and W were artificially inflated to unrealistic values.

While the potential importance of Φ_{HV} is becoming more apparent, the best approach for measuring $(\phi_H - \phi_V)$, from which Φ_{HV} is derived, remains to be determined. When using linear (horizontal and vertical) polarizations, $(\phi_H - \phi_V)$ must be calculated from the cross-correlation between vertically co-polarized (E_{VV}) and horizontally co-polarized (E_{HH}) signals separated in time by one or more interpulse periods (Jameson and Mueller, 1985; Sachidananda and Zrnic', 1986a) [One can also derive $(\phi_H - \phi_V)$ from simultaneous co- and cross-polarized signals (Jameson, 1985), but in rain the cross-polarized signals will often be very weak and, therefore, noisy.] During the interpulse period the precipitation moves producing a change in the phases of the signals. Although Jameson and Mueller (1985) and Sachidananda and Zrnic' (1986a) argue that this phase shift can probably be eliminated after sufficient averaging, for realistic finite sampling times there is likely still to be some slight residual phase noise.

Using circular polarizations $(\phi_H - \phi_V)$ can be estimated from simultaneous measurements of the co- and cross-polarized signals (Jameson and Hermant, 1987). Hence, the potential source of phase noise from particle velocities is eliminated. In addition from circular polarization measurements it appears possible to derive ζ unbiased by propagation effects (Bebbington et al., 1987; Jameson and Hermant, 1987).

Experiments, however, are required to determine which methods, circular or linear, are best. This can be achieved by interweaving from pulse to pulse nearly simultaneous linear and circular polarization measurements. The only radar in the Western world with this capability is the 5.45 cm wavelength DFVLR radar operating in Oberpfaffenhofen, Federal Republic of Germany. The P.I. is presently working with DFVLR scientists. Although comparisons such as these were intended to be part of the Phase I effort, the polarimetric switch on the DFVLR radar is undergoing modification so that these measurements will not be possible until 1988. It is recommended, therefore, that these investigations be pursued during Phase II.

4.2 Microwave Link Measurements

The most important role of a microwave link is the measurement of attenuation simultaneously at several frequencies. The attenuation measurements provide information directly relevant to the interpretation of scattering and emissivity of rain at the frequencies proposed for satellite radiometric observations. Measurement at multiple frequencies is not possible on any known single radar system sampling the same volume simultaneously. Attenuation and phase measurements along a microwave link can also provide several simultaneous estimates of the rainfall rate in still air (R_0).

An obviously desirable measurement is the path integrated attenuation (A_L) at a frequency near 35 GHz. It has been argued (Atlas and Ulbrich, 1977) that A_L is directly proportional to R_0 . Since at

this frequency the attenuation by rain is so strong, A_L at 35 GHz will be particularly useful in cases of light rainfall. However, at this frequency attenuation by water vapor is also significant with respect to that arising at rainfall rates less than 10 mm hr^{-1} (Hinkle, 1987). The proper estimation of the component due to precipitation requires some means for estimating the contribution due to water vapor. This is perhaps best achieved by the inclusion of phase shift and attenuation measurements at a frequency of 25.35 GHz (Hinkle, 1987). In the absence of moderate rain, the difference in phase shift [or more precisely the relative phase dispersion $\Delta\Phi_{ij} = \phi_j - \phi_i (\lambda_i / \lambda_j)$] between 25 GHz and the smaller frequencies provides a measure of the path integrated water vapor content (Hinkle, 1987). When moderate to heavy rain is also occurring, then both the phase dispersion between two frequencies and the attenuation at one frequency yield two equations with two unknowns (R_0 and the path integrated water vapor content). In a simplified form (after Hinkle, 1987) these equations are

$$A = A(R_0) + A(\text{vapor}) \quad (19a)$$

$$\Delta\Phi = \Delta\Phi(R_0) + \Delta\Phi(\text{vapor}) \quad (19b)$$

where A is the integrated attenuation along the path due to rain and to water vapor and $\Delta\Phi$ is the phase dispersion between frequencies. The procedure proposed by Hinkle (1987) is to estimate $A(\text{vapor})$ from standard meteorological measurements and then to estimate R_0 from (19a). Inserting this estimate of R_0 into (19b) yields an estimate of the integrated water vapor along the path. With this estimate of water vapor, $A(\text{vapor})$ can be adjusted and the whole process repeated until stability is reached. Using more than one combination of frequencies it should be possible to derive at least two different estimates of R_0 by this procedure.

An alternative estimate of R_0 which is independent of the approach described in (19) can be derived using $(\phi_H - \phi_V)$ (Sachidananda and Zrnic', 1986b). Differential phase shift can be measured by simultaneously transmitting horizontally and vertically polarized signals using two slightly separated frequencies at, say, 8 GHz. Rather than estimating R_0 , $(\phi_H - \phi_V)$ combined with an estimate of R_0 from (19) to yield the mass weighted mean raindrop axis ratio (β) using (18) (substituting β for R), assuming that the drops are equilibrium shaped. This estimate of β can be used to monitor the magnitude of the effect of shape on the attenuation and relative phase dispersion. It can also be used to estimate a mass weighted mean drop diameter which can then be compared with disdrometer measurements, if available.

In summary the advantages of a multiple frequency, dual polarization microwave link are that it can provide several independent or nearly independent simultaneous estimates of rainfall using attenuation and phase measurements along the path. Since these additional estimates involve different assumptions, fair confidence can be placed on an estimate of R_0 if these different techniques yield the same value. On the other hand, if the estimates differ, comparison with raingage measurements should help to identify the most accurate technique. By using a wide range of frequencies, measurements in

rainfall rates from about 1 mm hr^{-1} to greater than 100 mm hr^{-1} should be possible. Such a facility could provide a unique standard of comparison for rainfall estimation techniques proposed for satellites. It could also lead to the identification of suitable microwave link techniques for monitoring rainfall for urban and agricultural hydrological purposes more reliably and effectively than is possible using an extensive and expensive network of raingages.

5. Summary of Findings and Recommendations

1. Finding: While the summation phase shift ($\phi_H + \phi_V$) cannot be measured by radar, propagation differential phase shift can. Propagation differential phase shift ($\phi_H - \phi_V$), therefore, provides a drop size distribution independent estimate of the rain water content and rainfall rate in still air. Estimates from ($\phi_H - \phi_V$) can be compared with alternative radar estimates which while more readily measured are also affected by drop size distribution variability.

Recommendation: The development of propagation differential phase shift for the radar monitoring of rainfall should be vigorously pursued. This development must include research to identify the optimum polarization (both circular and linear) techniques for estimating ($\phi_H - \phi_V$) and comparisons with other radar estimation schemes. This is best achieved by continued use of the unique DFVLR radar in collaboration with DFVLR scientists.

2. Finding: A coherent multiple frequency, dual polarization microwave link can provide a unique facility for increasing our understanding of the potential and limitations of the remote sensing of rain. The inclusion of many frequencies will permit several simultaneous estimates of rainfall over a wide range of rainfall rates. Measurements at frequencies proposed for use on satellites should provide data for the development of improved radiometric rainfall algorithms. A bonus provided by the additional frequencies is the capability for measuring path integrated water vapor content.

Recommendation: A prototype microwave link for rainfall measurements should be designed and built. The development of this facility could, at a minimum, provide a unique standard of comparison for remote sensing techniques such as those proposed for satellites and radars. The best microwave link remote sensing techniques, when fully developed, might also provide irreplaceable hydrological information at locations not readily amenable to raingage networks.

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